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Towards the "third wave": An SCO-enabled occupational health and safety management system for construction

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ABSTRACT

Occupational health and safety (OHS) is of the utmost concern in the construction sector. For decades, researchers and practitioners have endeavoured to enhance construction OHS performance through various measures ranging from "hard" technologies (in this paper, the "first wave" of construction OHS management) such as provision of personal protective equipment, to the more recent "soft", managerial approaches (the "second wave") such as fostering a safety culture. Although considerable improvements have been made in construction OHS, the general sentiment is that construction remains one of the most dangerous sectors, warranting more innovative or even revolutionary approaches. This research seeks to develop a smart construction object (SCO)-enabled OHS management system. The central tenet of the system is that artificial intelligence (AI), as the art of creating machines that perform functions that require intelligence when performed by people, represents a direction of the "third wave" in construction OHS management. The system embraces emergent SCOs and harnesses the power of their smart properties of awareness, communicativeness, and autonomy. The system is demonstrated and validated in real-life construction practice and a controlled lab test with a tower crane, the cause of many construction-related injuries and fatalities, as the subject. It is found that the SCO-enabled OHS management system can identify dangerous situations and respond to them autonomously. This research suggests that smarter construction, through incorporation of AI in particular, is a direction of much promise in terms of improving construction OHS.

1. Introduction

According to the International Labour Office (2001), OHS management refers to a coordinated and systematic approach undertaken by an organization to protect the safety and health of all members through prevention of work-related injury, illness and disease. Despite strenuous efforts to manage OHS in the construction industry, its safety performance is still alarmingly poor. In the United States, for example, construction accounted for no more than 5% of the workforce but 20% of occupational deaths in the years 2003–2013 (National Safety Council, 2015). This disproportionate pattern is similar or worse in developing economies (Raheem and Hinze, 2014). It is estimated that a total of 60,000 construction fatalities occur every year around the world; on average, one every nine minutes (Somavia, 2005). The construction industry, while "instrumental in influencing human health, economic activities and social behaviour as well as cultural identity and civic pride" (Pearce, 2003), is also one of the most dangerous.

Efforts of researchers and practitioners to improve construction OHS management have been ongoing across several historical stages of development. The early days of OHS management can be characterised by a reliance on "hard" protection, using personal protective equipment (PPE) as a physical buffer between users and hazards. This was termed the "first wave" of OHS management in this paper. With the growing attentions on the root causes of accidents, a "second wave" of construction OHS management arises with the emphasis on safety training and safety education to reduce unsafe behaviours and dangerous situations. While considerable progress has been achieved during the first and second waves, often insufficient for making rational decisions and taking appropriate action when dangers suddenly emerge, making alerts ineffective. As a consequence of such limitations, construction

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around the world is witnessing stagnant OHS management. Inspired by smart technologies (e.g., artificial intelligence [AI], robotics) in other sectors, the construction industry is also vigorously exploring how these technologies as having the capacity can provide a revolutionary approach to improving OHS management in construction. This AI-based OHS management is to be argued as the "third wave" development in construction. However, the understanding of this "third wave" is in its infant stage. For example, there are exhortations to develop full "AI", or totally disruptive solutions to construction OHS management, while the take-up of these advocacies is rather low in reality.

Building on previous studies of smart construction objects (SCOs), the primary aim of this research is to (a) develop a SCO-enabled construction OHS management system, and (b) argue that SCOs augment construction resources with a "narrow AI" should be the "third wave" development of construction OHS management. Central to the "third wave" of construction OHS management is not completely departing from existing OHS management methods. While acknowledging the adoption of PPE and importance of preventive strategies, an active AI-based solution is proposed with the deployment of smart construction objects (SCOs). While SCOs provide OHS-related decision-making information to human decision-makers, they can also talk to each other directly. Thus, actions that can eliminate a hazard at source can be taken by SCOs promptly and autonomously; that is, without necessarily involving human decision-makers in the loop.

The remainder of this paper comprises seven sections. Subsequent to this introductory section is a review of the literature on the revolution of construction OHS management. By introducing the definition and properties of SCOs, the potentials and advantages of using SCOs for OHS management are presented in Section 3. In Section 4, the architecture and workflow of an SCO-enabled OHS management system is presented. With a tower crane selected as the target, the system is prototyped and validated in the context of a real-life on-site project in Section 5. A lab experiment is also presented demonstrating the system and how the SCO-enabled OHS management framework could be used in management strategy development. Section 6 discusses the prospects and challenges of the SCO-enabled OHS management framework, and conclusions are drawn in Section 7.

2. The three "waves" development of construction OHS management

The early days of OHS management can be characterised by a reliance on "hard" technologies, which is termed as the "first wave" OHS management in this paper. The protection is mainly relied on physical buffers provided by personal protective equipment (PPE) such as safety helmets, boots, gloves, and goggles (Hinze et al., 2013). Fundamentally, PPE work in the way of imposing a barrier between the user and the working environment, thus reducing the user's exposure to hazards including physical, electrical, heat, chemicals, biohazards, and airborne particulate matter. The "first wave" OHS management is not uniquely used in construction. A cross-sectoral analogue is the automotive industry, where car manufacturers have adopted physical protection (e.g. safety belts, air bags, and anti-lock braking systems) to protect drivers and passengers.

Despite the widespread applications of PPE in construction and continuing advances in technological approaches to its provision, a general limitation of PPE is that it does not eliminate hazards at their source (Holt, 2008). Thus, significant efforts have been directed in recent years to investigating the root causes of accidents. Heinrich (1941), a pioneer in accident causation investigation, developed the domino theory, which states that injuries occur as a result of linear, sequential factors. Building on this theory, enriched causation models incorporate factors such as unsafe conditions, unsafe behaviour and worker response (Abdelhamid and Everett, 2000). Managerial approaches to tackling these causes have also been explored, such as developing a behaviour-based safety system (Choudhry and Fang, 2008), conducting safety training (Hadikusumo and Rowlinson, 2002), and fostering a safety culture (Mohamed, 2003) and climate (Hahn and Murphy, 2008). These efforts echo developments attributing accidents largely to overload of human capabilities, both physical and psychological, such as the human-error causation model (Petersen, 1984) and the DeJoy (1990) model. While unavoidably intertwined with traditional technological approaches, such efforts focus on "soft" aspects and can be collectively referred to as the "second wave" in OHS management. As in the case of "hard" technologies, an emphasis on "soft" aspects can also be found in the automotive industry, for example through safe-driver education and the enforcement of strict traffic rules and regulations.

While human error-related accidents can be reduced with safety training and safety culture development, they cannot be completely eliminated due to unexpected conditions such as fatigue or sudden site distractions (Fang et al., 2015). Studies have been made for safety management systems using emerging technologies, most of which focus on detecting hazardous conditions and issuing alerts. For example, sensing technologies such as Radio Frequency Identification (RFID) (Lu et al., 2011; Flanagan et al., 2014) and wireless networks such as ZigBee have been used to capture real-time construction site conditions (Wu et al., 2010), while cyber-physical systems have been developed to model the complexities of construction safety (Yuan et al., 2016). Alerts can be issued when people enter pre-defined danger zones (Yang et al., 2012) or are too close to moving objects (Teizer et al., 2010).

However, the safety protection provided by these technologies is imperfect. Although timely alerts can be provided, in-time mitigations and actions in response to dangerous situation still largely rely on humans. Researchers have theorized OHS management as decision making, recognizing that the rationality of human decision-makers (e.g. safety managers and construction workers) is generally bounded by a "triangle of limits" (Simon, 1976): available information, cognitive ability, and finite amount of time. The latter is often insufficient for making rational decisions and taking appropriate action when dangers suddenly emerge, making alerts ineffective. Thus, a more intelligent, in-time solution is desired to manage OHS events proactively and promptly.

The development of construction OHS management, toward the next wave, could draw inspiration from the automotive industry. Smart systems such as self-parking and collision prevention assistants are now embedded in cars to improve driving safety, for example by detecting hazardous conditions and alerting drivers. These smart systems are enhanced with artificial intelligence (AI) in auto-pilot systems (e.g. as in Tesla vehicles) (Kessler, 2015) and autonomous vehicles (e.g. Apple self-driving cars) (Harris, 2015). Since movement on the road is no less complex than on a construction site, there are no barriers to the exploration of AI in construction OHS management. It is thus proposed the "third wave" of construction OHS management, in this study, subscribes to AI-based solutions. It acknowledges that human beings are not infallible, but rather, show deficiencies (such as being slower and more error-prone) when compared with AI in processing information and making prompt actions (Sterman, 1989; Reason, 2000).

3. SCOs for OHS management

Proposed by Niu et al. (2015), smart construction objects (SCOs) represent a new way of capturing, processing, and communicating information to support decision making in construction. SCOs are "construction resources (e.g., machinery, tools, devices, materials, components, and even temporary or permanent structures) that are made smart by augmenting them with sensing, processing, and communication abilities so that they have autonomy and awareness, and can interact with the vicinity to enable better decision making" (Niu et al., 2016). Instead of introducing a completely new system to construction sites, an SCO-enabled management system relies on construction objects (such as machines, materials and components) already involved in